AD-A146 560 A BRIEF INVESTIGATION INTO THE VALIDITY OF SEASAT RADAR ALTIMETER DATA ACQUIRED OVER LAND(U) NAVAL RESEARCH LAB WASHINGTON DC D M HORAN ET AL. 26 SEP 84 NRL-MR-5419 1/1

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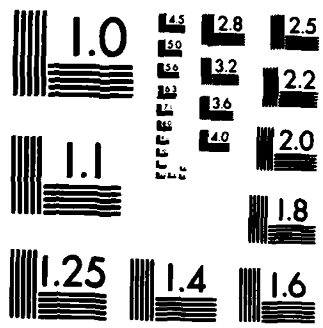

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NRL Memorandum Report 5419

A Brief Investigation into the Validity of SEASAT Radar Altimeter Data Acquired Over Land

D. M. HORAN AND L. W. CHOY

Space Sensing Applications Branch
Aerospace Systems Division

September 26, 1984

This project was funded jointly by the Naval Air Systems Command and the Office of Naval Research.

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECUR CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5419	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory — 6b OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION NAVAIR and ONR — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20361 Arlington, VA 22217	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. (See page ii) — PROJECT NO. — TASK NO. — WORK UNIT ACCESSION NO.

11 TITLE (Include Security Classification)

A Brief Investigation into the Validity of SEASAT Radar Altimeter Data Acquired Over Land

12. PERSONAL AUTHOR(S)
Horan, D.M. and Choy, L.W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Interim	FROM 3/83 TO 5/84	1984 September 26	28

16 SUPPLEMENTARY NOTATION

This project was funded jointly by the Naval Air Systems Command and the Office of Naval Research.

17 COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Satellite altimetry Terrain profiling

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The SEASAT 1 satellite, which was launched in 1978, carried a radar altimeter which was optimized for operation over the open ocean. However, the instrument did make a significant number of measurements while over land. It is conclusively demonstrated that the radar altimeter serendipitously made measurements over relatively flat terrain which can provide accurate ground elevations. In addition, it is possible that the instrument had some capability to distinguish ground features such as canals, elevated roads, and power lines.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL D. M. Horan	22b TELEPHONE (Include Area Code) (202) 767-2778 — 22c. OFFICE SYMBOL Code 7910

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
63207N	W05270S	A33033OH/058C/	DN680-370
63371N	R1452-SB-00	4W0527-0S00	DN280-135

CONTENTS

A BRIEF INVESTIGATION INTO THE VALIDITY OF SEASAT RADAR ALTIMETER DATA ACQUIRED OVER LAND

SEASAT RADAR ALTIMETER CHARACTERISTICS

The SEASAT 1 satellite was launched on 27 June 1978 and carried sensors of various types designed to measure sea conditions. One of the sensors was a radar altimeter which successfully demonstrated the capability to monitor ocean wave height and wind speed and to accurately measure the range to the ocean surface. Townsend (1980) described the design and operation of the altimeter and presented an evaluation of the instrument's initial performance. The altimeter was a monostatic radar system which operated at 13.5 GHz and sent pulses in the nadir direction at a pulse rate of 1020 Hz. The instrument's on-board data processor adjusted the time delay associated with a set of 61 contiguous electronic gates so that the rising half-power point of returning pulses would enter the middle gate. Each gate represented a 3.125 ns time delay. Two additional gates bracketed the middle gate to help define the rising half-power point of the returning pulses. The response to each returning pulse in the set of gates created a waveform. The data processor set the time delay for the contiguous gates based on composite return waveforms generated by groups of 50 pulses. The electronic control which kept the waveforms properly placed within the set of gates was designed for the gradual altitude changes encountered over large bodies of water. The large and rapid altitude changes usually encountered when the satellite was over land caused the returning pulses to miss the set of gates and the altimeter then lost lock. Lock could not be reacquired until the sub-satellite point returned to a region of gradually changing elevation. However, the altimeter demonstrated the capability for maintaining or reacquiring lock over terrain which was relatively flat, such as arctic ice and snow fields, deserts, and the Everglades region of Florida. When lock was maintained, whether over water or land, the data processor calculated the height of the spacecraft above the Earth's surface approximately once every 0.1 second based on return waveforms from 100 pulses taken as two groups of 50 pulses each. The calculated height data and the composite waveform generated from the 100 pulses were transmitted at intervals of approximately 0.1 second.

REFERENCE SURFACE ELEVATIONS

The high quality of the altimeter data collected over water and earlier analyses of overland data from SKYLAB (Shapiro, et al., 1975) and from GEOS 3 (Miller, 1979) inspired interest in the significant quantity of data obtained while SEASAT was over land. An opportunity to make a brief investigation of the validity of the SEASAT overland data finally presented itself in early 1983. Data from several passes were reviewed to find a pass with a large segment during which the altimeter maintained lock while passing over land. A portion of pass 515 of 2 August 1978 was selected in which the satellite passed over Florida from 28.2°N, 80.6°W to 25.9°N,

Manuscript approved June 13, 1984.

81.7°W. The length of the ground track was approximately 295 kilometers. The satellite's ground track across Florida was plotted on 1:24000 scale topographical maps provided by the U.S. Geological Survey. The position of the satellite along the ground track at the indicated times of transmission of altitude and waveform data was marked on the maps. This resulted in a series of marks, approximately 700 meters apart, along the ground track of the satellite. The radar altimeter responded to energy reflected from an extended source on the Earth's surface. An estimate had to be made of the extent of the footprint on the Earth's surface associated with an individual pulse and the overall footprint affecting the telemetered altitude and waveform based on 100 pulses. As a first attempt at defining the overall footprint, it was decided to heavily weight the terrain extending approximately 0.6 kilometers in each direction perpendicular to the ground track and roughly 0.7 kilometers backward along the ground track from the point associated with the telemetering of the data. Figure 1 shows the weighted area associated with an overall footprint. Based on this weighting, an "eyeball average" was formed for the elevation of the overall footprint associated with each altitude data point telemetered from the satellite during the pass across Florida. This procedure was followed a second time after an interval of several days to obtain a second set of elevation values for comparison. The two sets of ground elevations obtained from the maps agreed extremely well and the first set was retained for use as a ground truth reference. Along the satellite's ground track the surface elevations obtained from the maps ranged from sea level to 23 meters.

CORRECTIONS TO SATELLITE DATA

Range data telemetered from the satellite had been processed to provide surface elevations with respect to a reference ellipsoid. These surface elevations were normalized to sea level off the east coast of Florida. An additional correction was necessary because the geoid changes rapidly across the Florida peninsula. This correction was made by subtracting an appropriate value from each surface elevation value based on a 5.2 meter change in the geoid, assumed to be linear, along the satellite track from the east to the west coast of Florida. A plot was made of the normalized and corrected surface elevations obtained from the satellite versus the distance along the ground track over which data transmission occurred. The surface elevations obtained from the topographical maps were plotted on the same graph. This revealed a general agreement between the two sets of data along the satellite's ground track, but also resulted in a sawtooth pattern in the telemetered data. The sawtooth pattern was irregular, had a peak to valley difference of approximately 6 meters, and caused an average difference between the telemetered and map elevations of about 3 meters.

Waveform data telemetered from the spacecraft at intervals of approximately 0.1 second were examined. It quickly became clear that for data points near the maximum and minimum of the sawtooth pattern, the rising half-power point of the waveform was displaced from its proper location in the middle gate and that the direction of the displacement shifted from early to late gates in phase with changes from valleys to peaks of the sawtooth patterns. Brooks (1983) pointed out that a displacement of the waveform by one gate from its proper location was equivalent to an error of 0.47 meter in the altitude value telemetered. A technique used to correct the telemetered data for this displacement of the waveform is described in

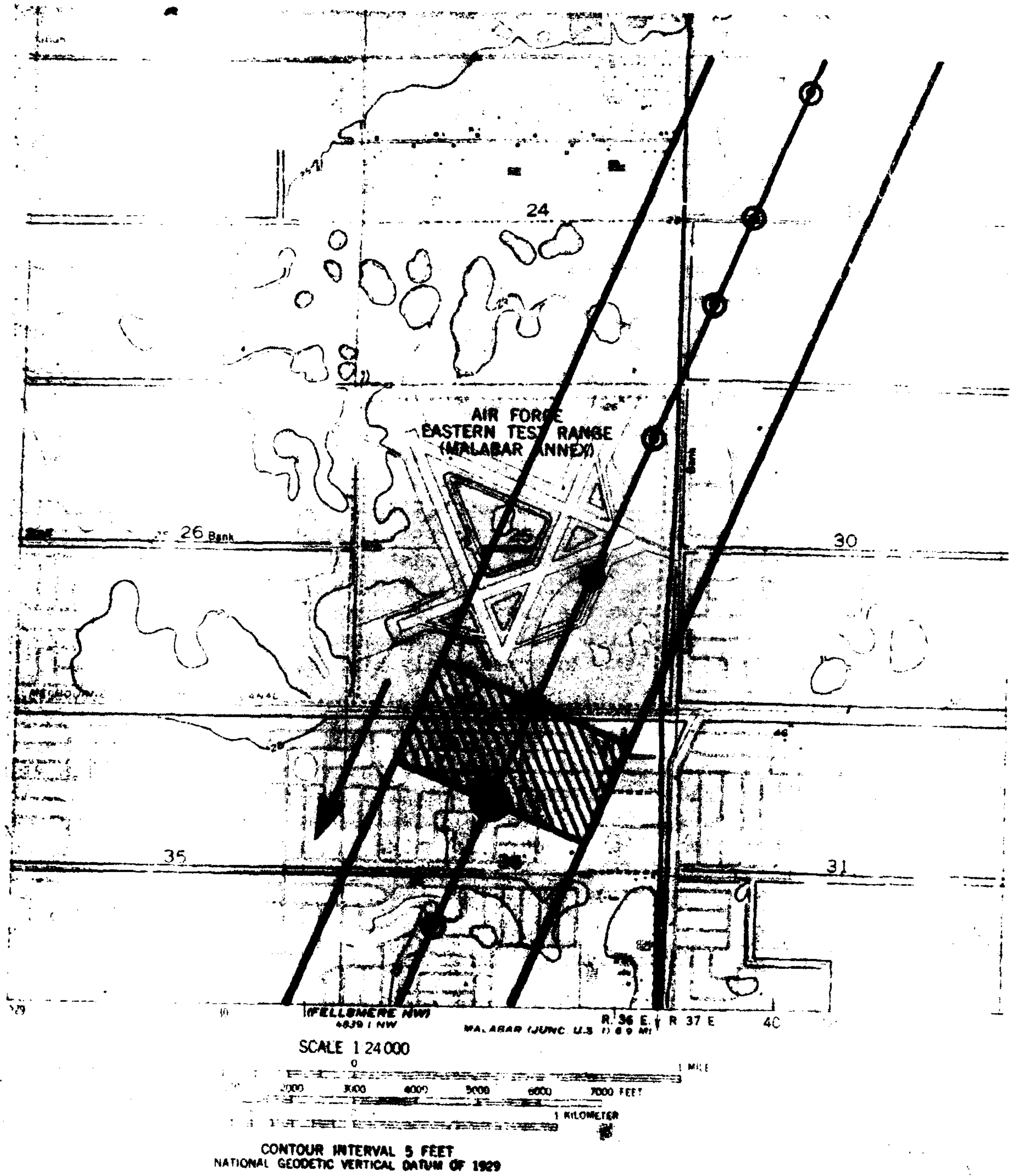

Fig. 1 The shaded area indicates the surface area assumed to have the greatest effect on the altitude data transmitted when the satellite was over the position indicated by the accentuated circle. Circled dots indicate other positions over which data transmissions were made at 0.1 second intervals.

Brooks (1981a, 1981b) and Martin, et al. (1983). A waveform properly located in the gates is shown in Figure 2. A waveform shifted toward the early gates, which caused the telemetered altitude value to be too large by 47 cm for every gate that the waveform was displaced, is shown in Figure 3. The correction for the displacement in Figure 3 is the subtraction of 1.2 meters from the measured altitude and the addition of 1.2 meters to the surface elevation. A waveform shifted toward the late gates, which results in an altitude value which is too small and a surface elevation value which is too large by 4.9 meters, is shown in Figure 4. Brooks (1983) also pointed out that the waveform which had been telemetered with a given altitude value is not the waveform which corresponds to that altitude value. The altitude values and waveforms transmitted are out of synchronization such that a given waveform corresponds to the altitude value transmitted 0.1 second earlier. After the waveforms and altitude values were properly synchronized and the surface elevation values corrected for displaced waveforms within the gates, the surface elevation values were again plotted with the ground truth elevation against the ground track of pass 515 across Florida (Figure 5). The satellite surface elevation data closely parallels the map data. The satellite data almost always indicates a higher ground elevation than obtained from the maps; the average elevation difference between the two sets of data is 1.13 meter with a standard deviation of 0.91 meter. However, no tidal correction was applied when the satellite data was normalized to the ocean's surface off the east coast of Florida and that could cause a constant error in the satellite data of a few feet or less in either direction. Also, when the terrain is rough or sloping, the higher elevations within the footprint will have a disproportionately large effect (Brenner, et al., 1983) giving an erroneously high elevation measurement.

The results of our brief investigation and the results obtained by Brooks and others (Brooks, 1980, 1981a, 1981b, 1982; Brooks and Norcross, 1982, 1983a, 1983b; Brooks, et al., 1982; Martin, et al., 1983) conclusively demonstrate that the radar altimeter on SEASAT 1 could make accurate measurements of ground elevation over relatively flat terrain. However, in the SEASAT configuration of the radar altimeter, it is essential that the waveform data be available so that the altitude values telemetered can be corrected whenever the waveform is not properly centered within the gates.

WAVEFORMS CONTAIN INFORMATION ON SURFACE FEATURES

In addition to providing a basis for correcting the altitude measurements from the radar altimeter, the waveforms contain information about the surface features within their footprints. Excepting the anomalously low value in gate 59, a typical waveform generated when the satellite was over open ocean is shown in Figure 6. The early gates, 1 through 28, show no response. The reflected energy of the radar pulses first appears in gate 29 and rises to a maximum in gate 32 because of the increasing illuminated surface area as the leading edge of the radar pulse struck the surface at greater distances from the nadir. The maximum response at gate 32 represents the attainment of maximum illuminated area when the trailing edge of the radar pulse arrived at the surface at the nadir. For a satellite which was 800 km above the surface, such as SEASAT, the leading edge of a pulse with a 12.5 ns duration would be about 1.7 km from the nadir when the trailing edge of the pulse arrived at the surface. The illuminated surface area remained constant but changed shape from a

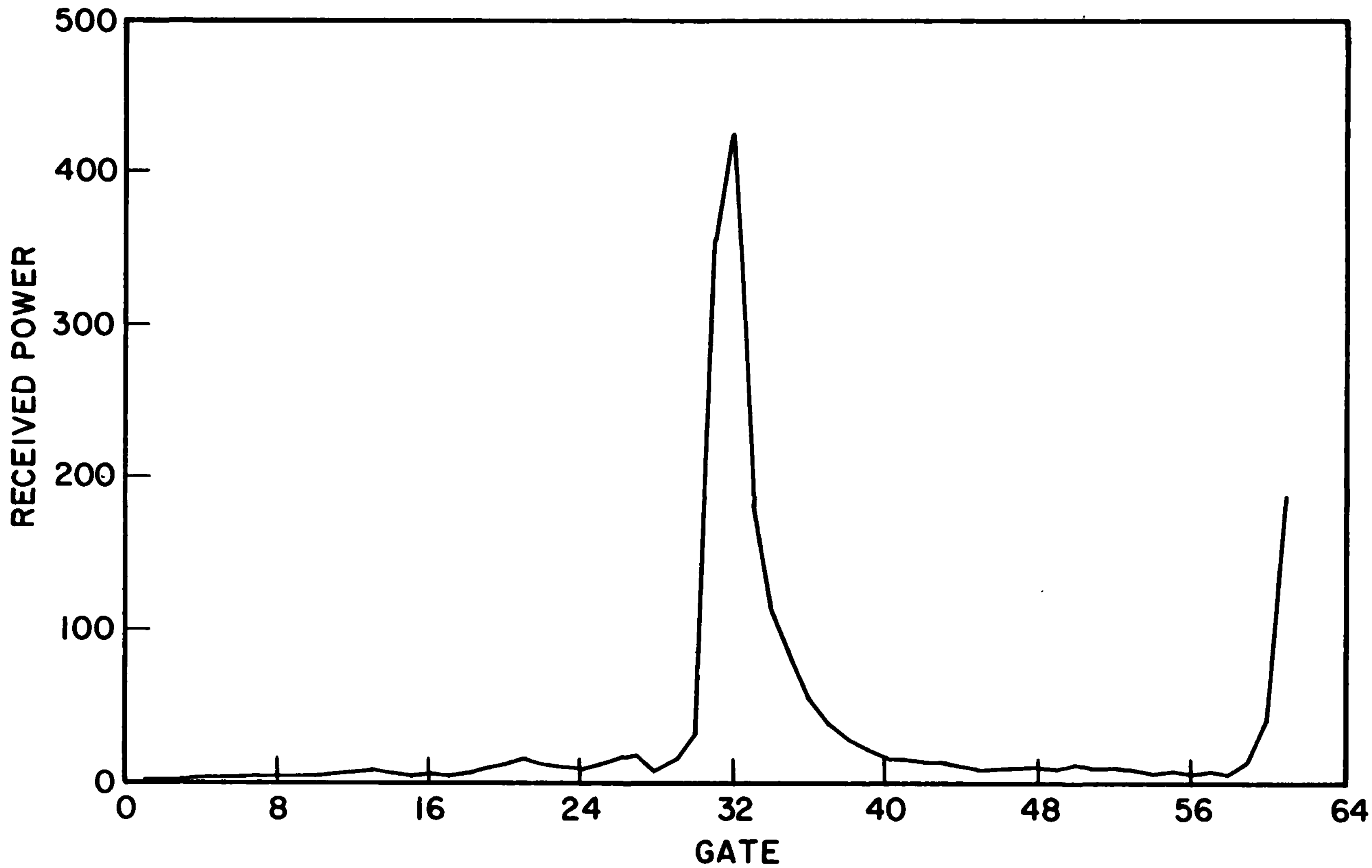

Fig. 2 A waveform shape typical of those generated by dry land (except for the increase near gate 60). Also, the waveform is properly centered within the set of gates.

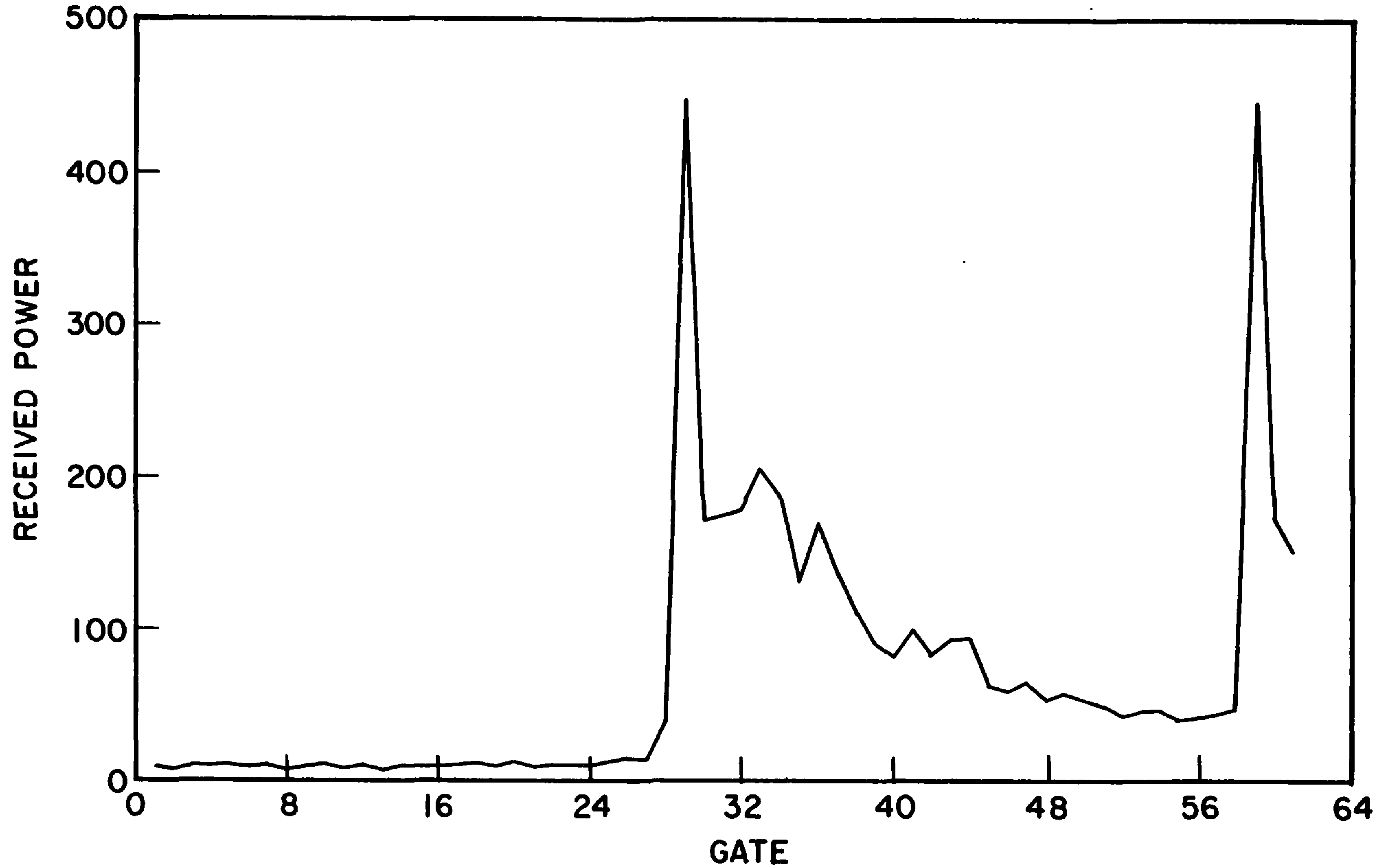

Fig. 3 A waveform not properly centered in the gates, but shifted toward the early gates. Altitude data based on this waveform required correction.

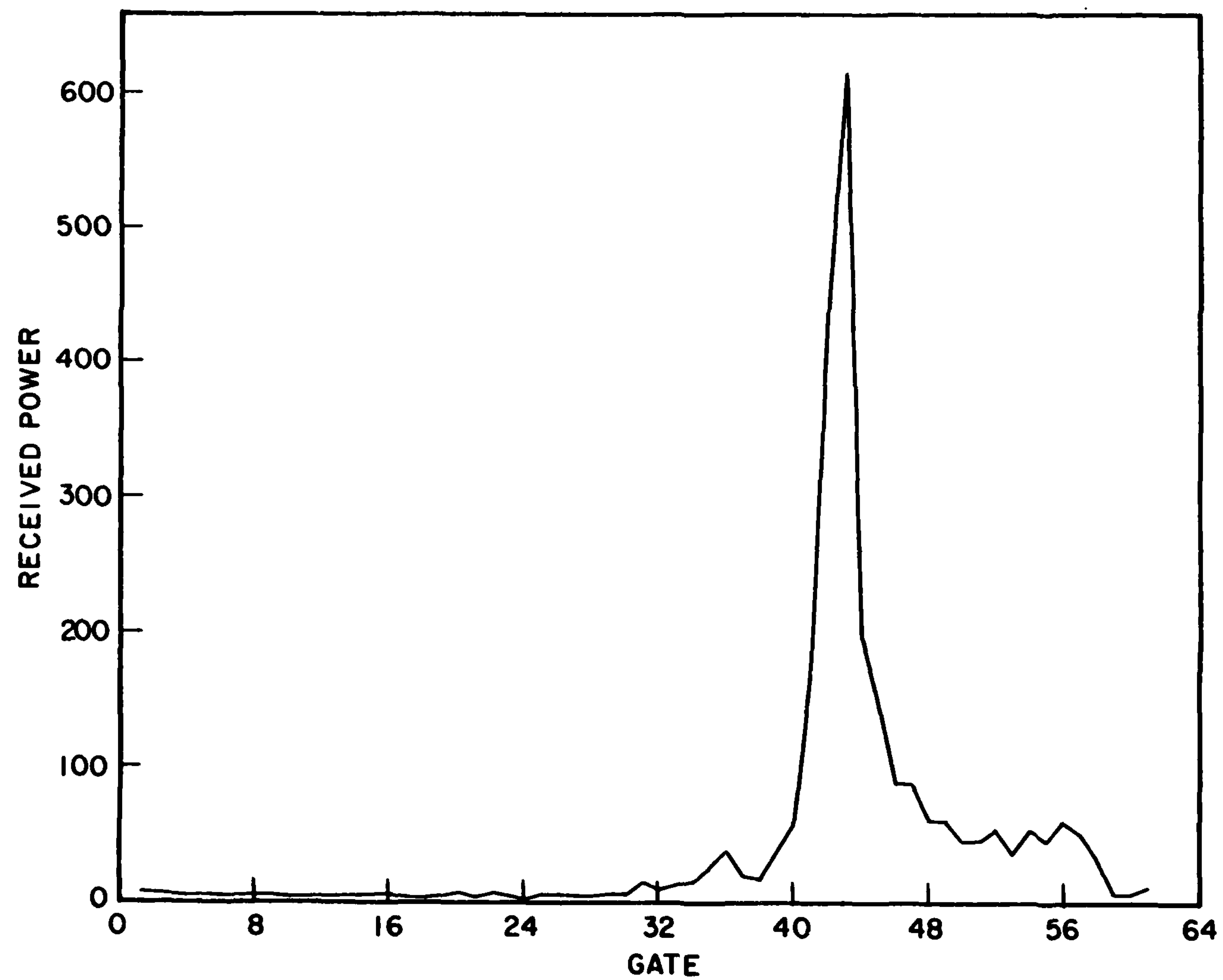

Fig. 4 A waveform not properly centered in the gates, but shifted toward the late gates. Altitude data based on this waveform required correction.

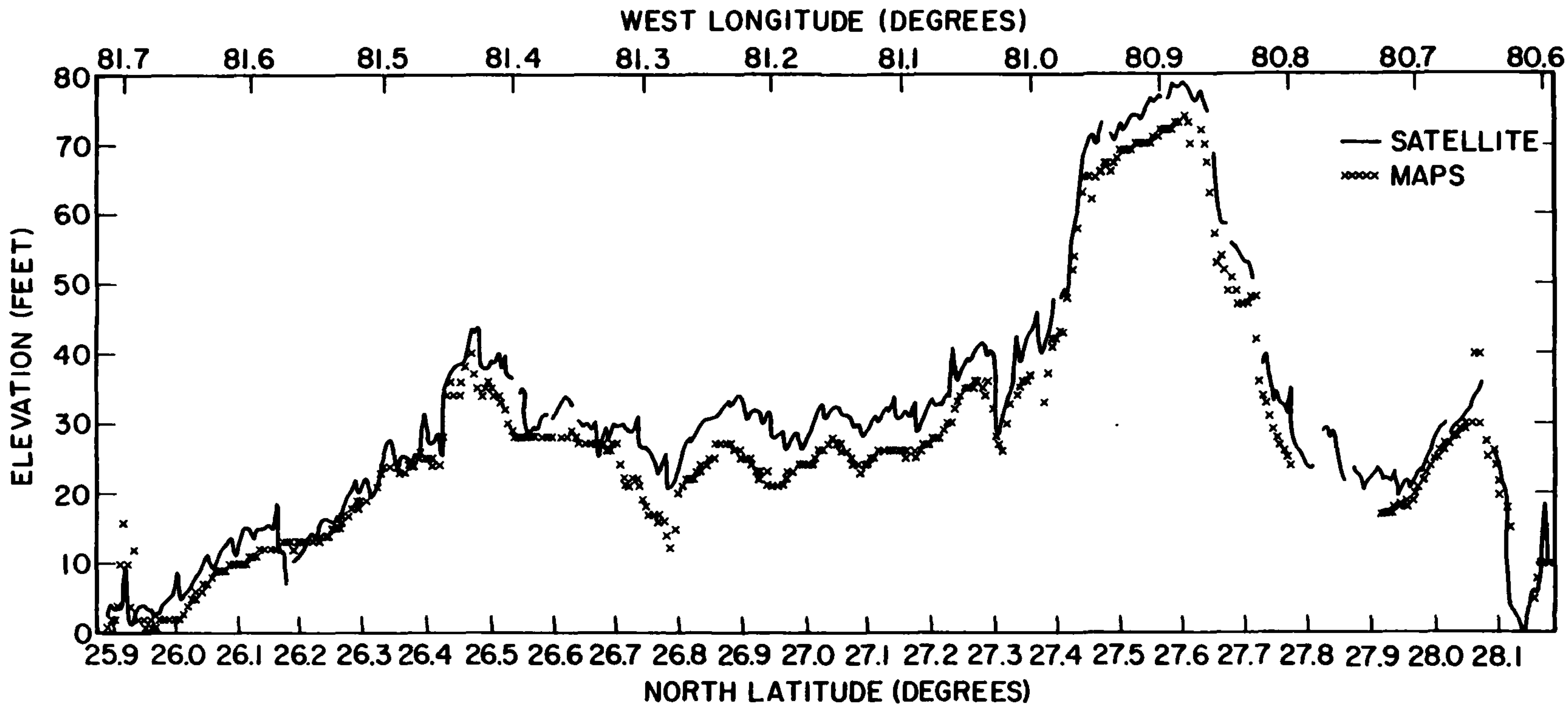

Fig. 5 Surface elevations derived from satellite data (solid line) and from topographical maps (xxxx line) versus the ground track of SEASAT pass 515 across Florida.

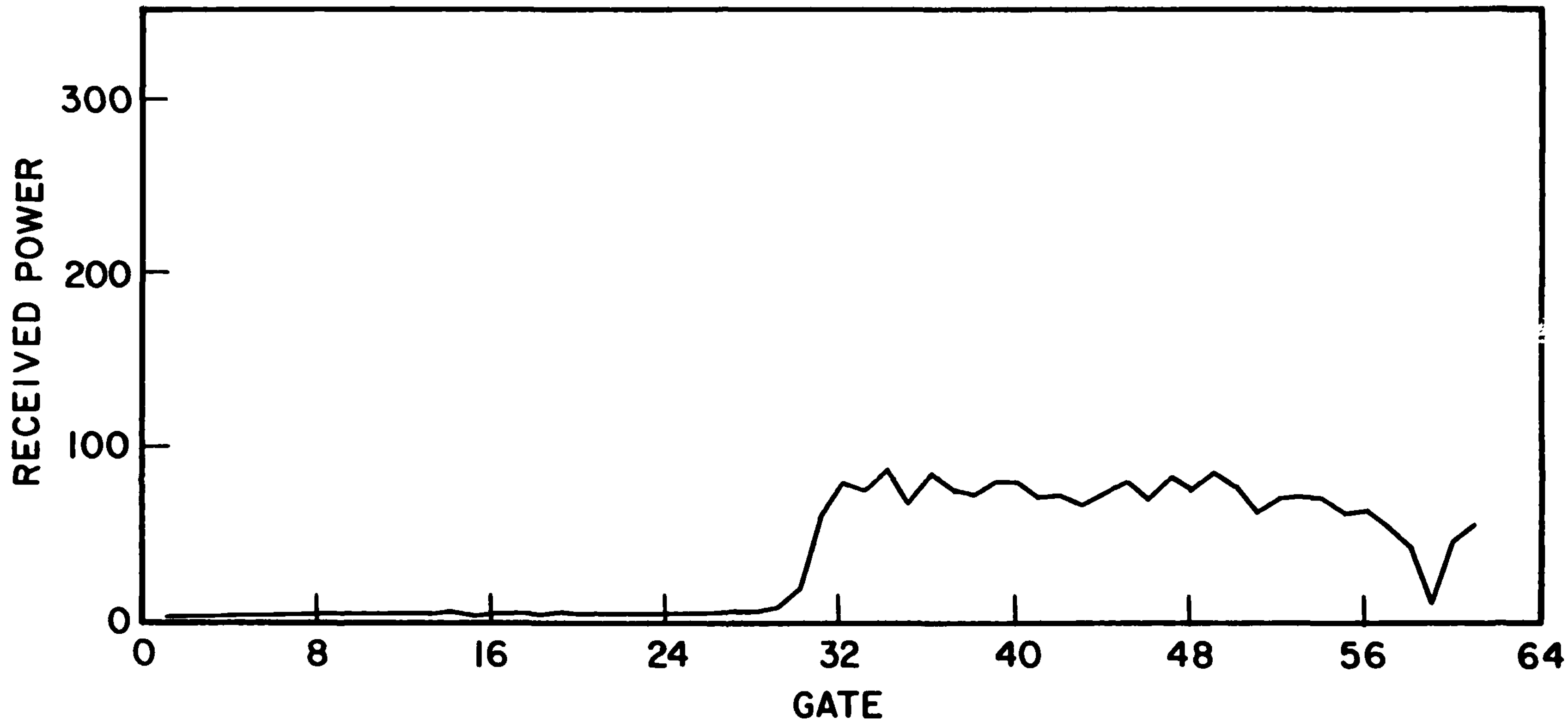

Fig. 6   A waveform shape typical of those generated by the open ocean.

circle to a ring as it spread outward from the nadir. Reflected energy from the spreading area of illumination entered increasingly later gates. The value for the altimeter's automatic gain control setting, which was telemetered with the altitude data, indicates that the ocean surface was a poorer reflector than flat, dry land. This was because the ocean surface, disturbed by waves and wind, significantly scattered the energy. However, this scattering of energy permitted the waveform to persist at near its maximum value until the final gate. Energy entering the final gate was reflected from surface points which were between 4.4 and 4.8 km from the nadir.

The waveform which is characteristic of reflection from flat, solid ground, Figure 2, is markedly different from the open ocean's waveform. Waveforms associated with dry land rise quickly to a maximum as the illuminated area increases but then drop off very quickly to near background levels in the later gates. This means that the energy reflected to the satellite was almost entirely from the vicinity of the nadir and decreased very rapidly as the illuminated area spread outward from the nadir. Therefore, the dry ground caused less scattering of the radar pulses than did the open ocean, and the footprint associated with a dry land waveform was much smaller than that associated with an open ocean waveform. The sharp rise in the response shown in Figure 2 over a span of no more than four gates followed by an immediate decrease can be interpreted as indicating that there was very little contribution from the illuminated area farthest from the nadir when the trailing edge first arrived at the surface. Therefore, the footprint associated with the waveform in Figure 2 was a circle of less than 1.7 km in radius. The automatic gain control settings associated with the dry land waveforms indicate that the signal reflected from the dry land was much stronger than the signal reflected from the ocean. The response in gates 59 through 61 of the waveform in Figure 2 is unusual and not understood. It may have been caused by energy from a distant, highly reflective surface which was tilted optimally to reflect energy to the satellite.

Structure in waveforms from dry land, both preceding and following the primary peak, contains additional information about reflecting surfaces beneath the spacecraft. For instance, Brooks and Norcross (1983b) have plausibly interpreted structure preceding the primary peak as trees and sawgrass in the Everglades. The collection of waveforms obtained over Florida during pass 515 produced many waveforms which showed interesting deviations from the characteristic waveform. Several examples were found in which the primary feature in the waveform is clearly a pair of central peaks, Figures 7 and 8. The waveform shown in Figure 7 is associated with altitude data telemetered when the sub-satellite point was at 28.013°N, 80.679°W. An examination of the Melbourne West map showed that the Melbourne Tillman Canal was within the illuminated area which produced the dual-peaked waveform. The first peak in the waveform was possibly generated by reflection from the solid ground, and the second peak may have been caused by reflection from the water surface in the canal. If so, the water level was about 4 meters below the local ground level. Brooks and Norcross (1983b) noted that calm water produced the strongest reflections. The surface of a canal depressed below local ground level could be significantly less disturbed than a typical extended open water area and thus could produce a strong reflection from a relatively small surface area. The

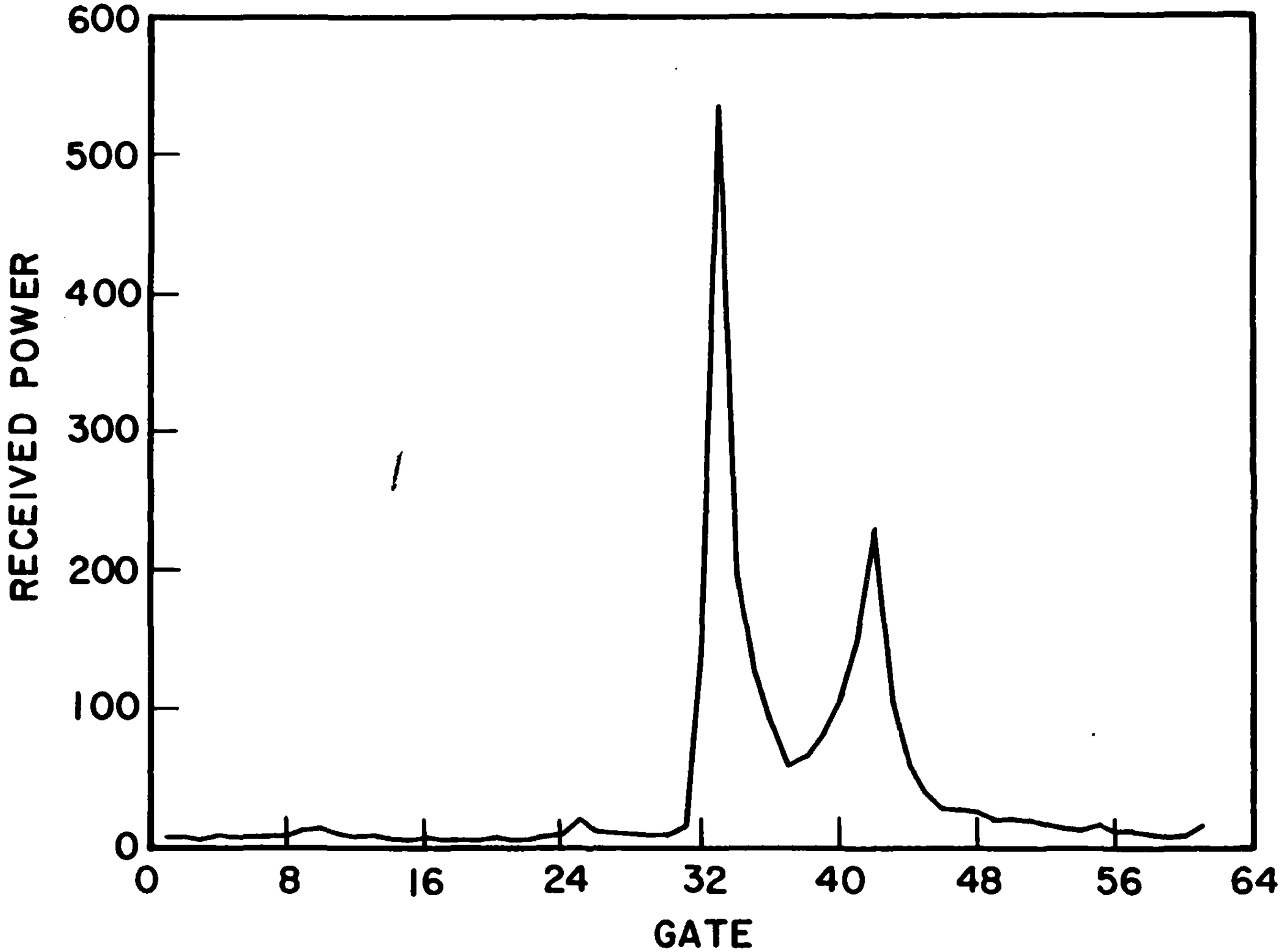

Fig. 7 The unusual double peak in the waveform may indicate the presence of a canal whose water surface is about 4 meters below the local ground level.

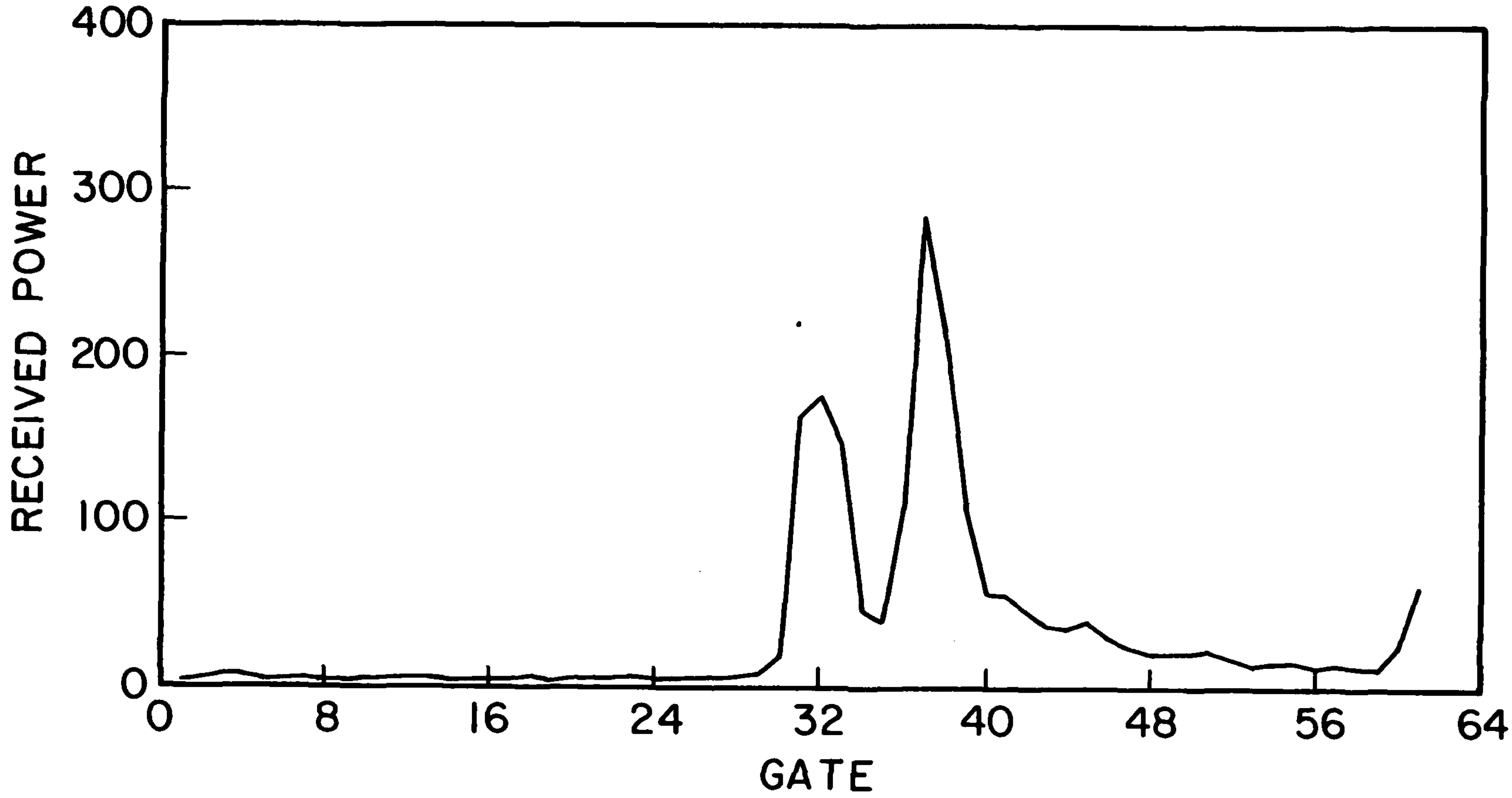

Fig. 8 The unusual double peak in the waveform may indicate the presence of a highway which is elevated about 2.5 meters above the local ground level.

Melbourne West map was made in 1949 and revised in 1980 based on aerial photographs taken in 1977.

The waveform in Figure 8 is associated with altitude data transmitted while SEASAT was over 27.644°N, 80.861°W. This location appears on the Fort Drum NE map which was made in 1953 and revised on the basis of aerial photographs taken in 1972. The footprint associated with the waveform in Figure 8 contained the Florida Turnpike, a dual highway toll road. The first peak in the waveform was possibly generated by reflection from the highway, and the second peak may have been caused by the ground surface. The elevation difference was approximately 2.5 meters, which seems reasonable for a road elevation above the ground surface on terrain which the map identifies as having marshy tendencies. Steel mesh and reinforcing rods used in highway construction could cause a strong reflected signal.

The waveform shown in Figure 9 has significant structure in gates 8 through 18 preceding the single central peak indicative of a dry ground footprint. The sub-satellite point associated with this waveform was at 28.040°N, 80.665°W, which appears on the Melbourne West map also. The map clearly indicates that a double power transmission line passed through this waveform's footprint. Since the map does not indicate the presence of power lines in residential areas, indicated power lines may be large, significant structures. If the response in gates 8 through 18 of the waveform was from power lines, then the power lines were between 9 and 12 meters above the ground.

A distortion of the central peak of the waveform is shown in Figures 10 and 11. Some structure in the waveform preceding the central peak appears in Figure 11. The waveform of Figure 11 immediately followed the waveform of Figure 10. Both footprints appear on the Melbourne West map with the sub-satellite point associated with Figure 10 at 28.068°N, 80.651°W, and that associated with Figure 11 at 28.062°N, 80.654°W. Both footprints contained residential areas, and thus it is possible that houses were the cause of the distortion in the central peak. Krabill and Brooks (1979) noted that suburban homes with sloped roofs did not affect the altimeter measurements made using a similar instrument on the earler GEOS 3 satellite. They did not mention possible distortion of the waveform, however. The distortions in the waveforms in Figures 10 and 11 did not affect the altitude measurements. The map shows that the housing development in the footprint associated with Figure 10 was on cleared ground, but the housing development in the footprint associated with Figure 11 was in a wooded area. The structure preceding the central peak in the waveform of Figure 11 was possibly caused by reflection from foliage between 9 and 15 meters above the ground.

The waveform shown in Figure 12, although obtained while the satellite was over land, is closer to a typical open ocean waveform than a typical dry land waveform. Even the automatic gain control setting associated with this waveform is consistent with a weaker reflected signal than would normally be encountered over land. The sub-satellite point for this waveform was at 26.188°N, 81.569°W, which is on the Belle Meade NE map made in 1958 and revised based on aerial photographs taken in 1973. The map shows that the footprint associated with this waveform was primarily wooded marshland. Possibly the water level was sufficiently high on 2 August 1978 that the

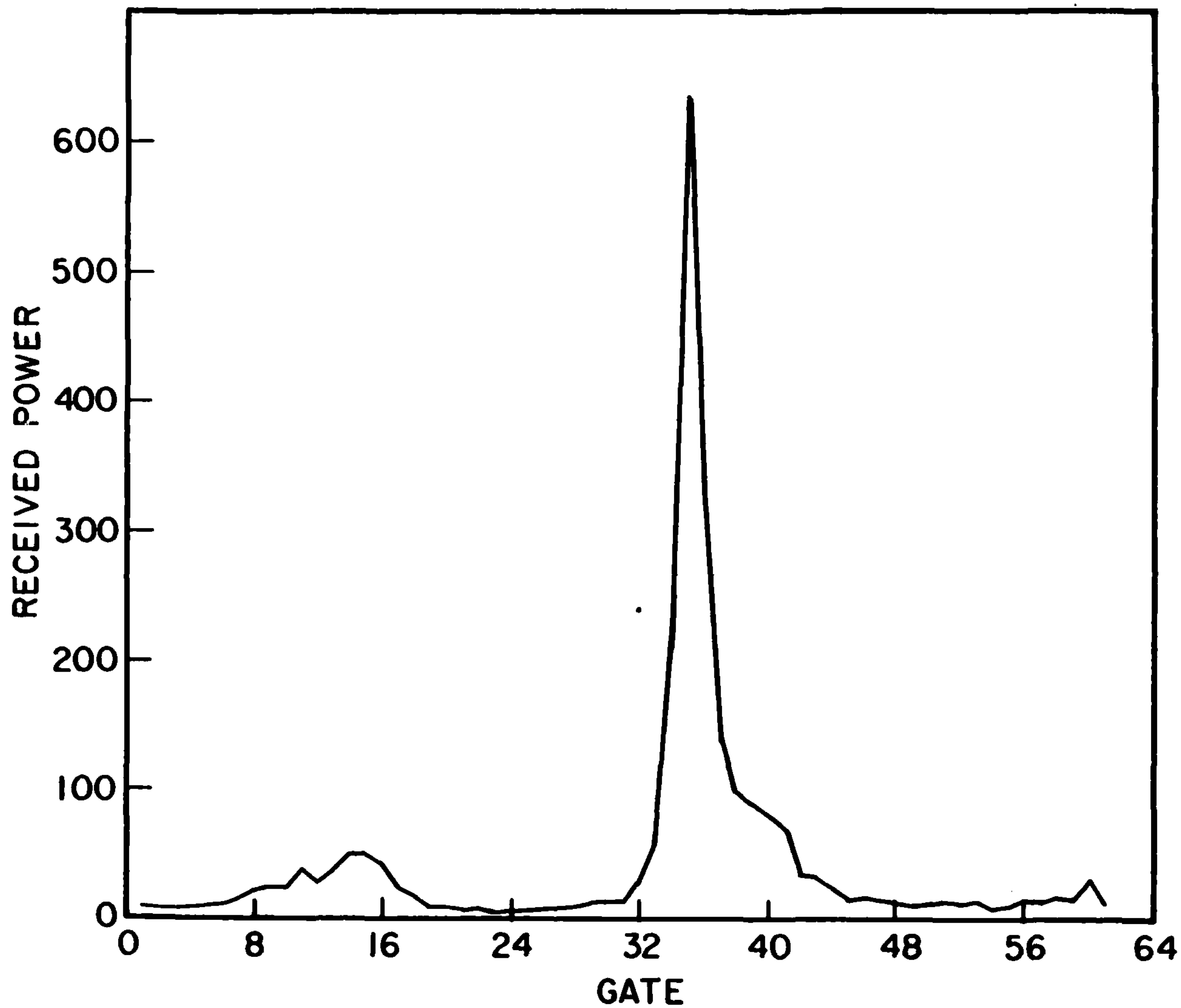

Fig. 9 The structure in the waveform between gates 7 and 18 may indicate the presence of power lines 9 to 12 meters above the local ground level.

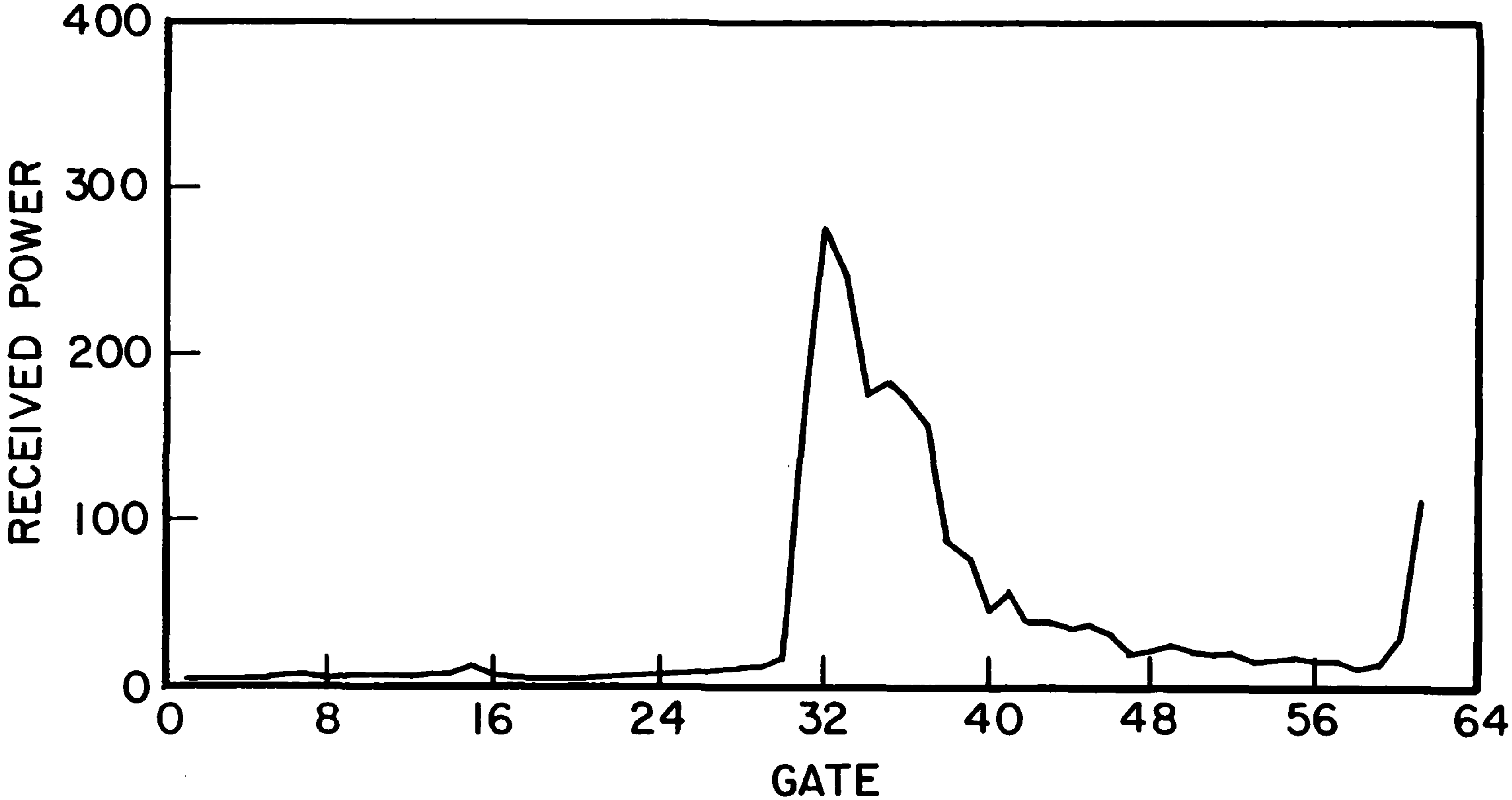

Fig. 10 The distortion of the central peak may be caused by houses.

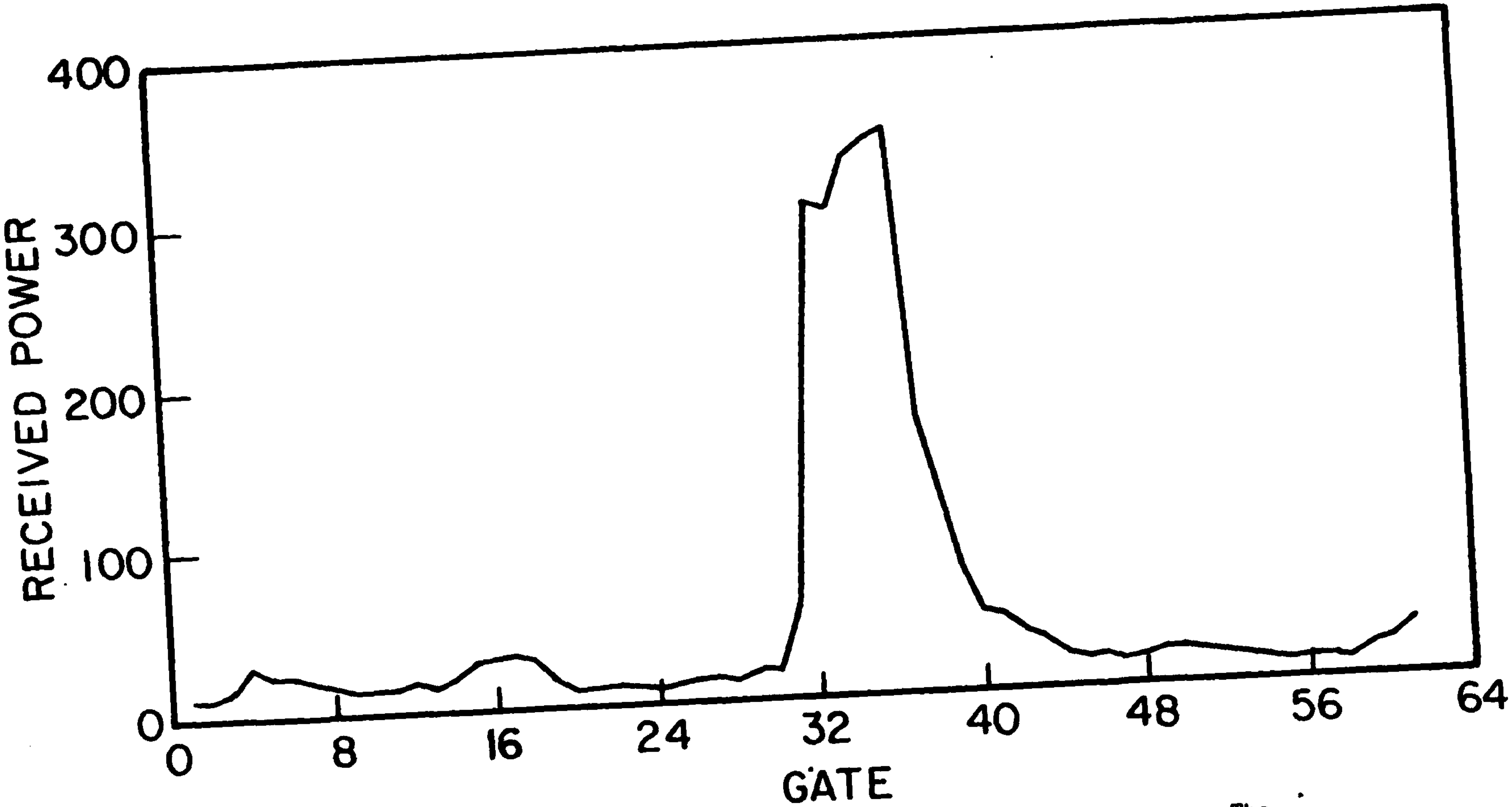

Fig. 11 The distortion of the central peak may be caused by houses. The structure near gates 4 and 16 may be caused by foliage which is 9 to 15 meters above local ground level.

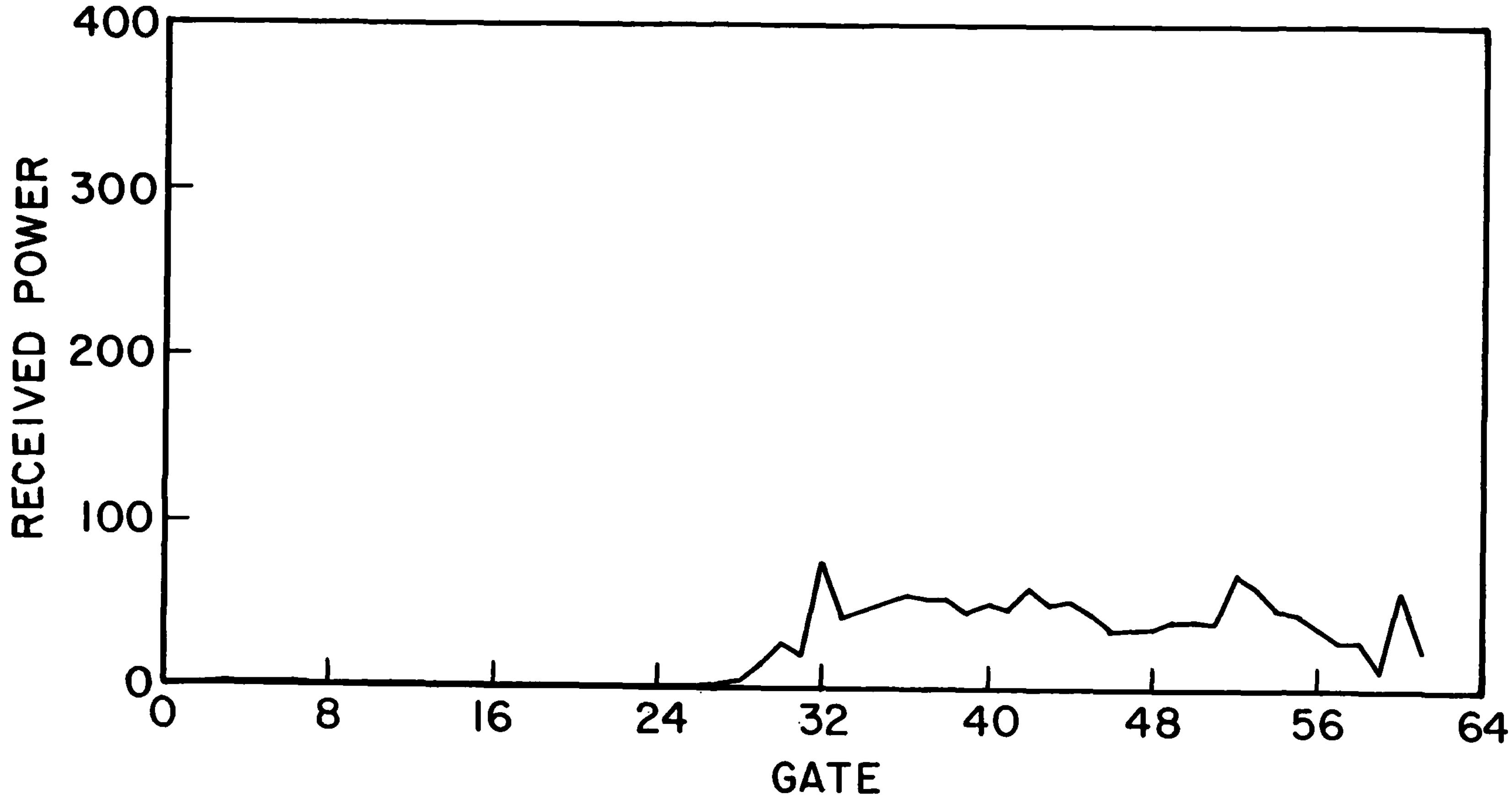

Fig. 12 The waveform, although obtained over dry land, has a shape which is more characteristic of those obtained over open ocean.

reflecting surface was almost entirely a water surface disturbed by wind, and thus the waveform took on characteristics of an open ocean waveform.

An unusual waveform associated with a sub-satellite point at 27.864°N, 80.752°W located on the Kenansville SE map is shown in Figure 13. The map was made in 1953 and revised based on aerial photographs taken in 1972. The footprint associated with this waveform was solidly within the boundaries of St. Johns Marsh and is identified on the map as marshland. Small ponds are indicated on the map in various sections of the marsh, but none are explicitly indicated near or within the footprint associated with this waveform. However, it is possible that the water level was different in 1978. The automatic gain control setting for this waveform was closer to values for dry land than for open ocean. The three peaks in the waveform could have been caused by reflections from quiet ponds and the structure in gates 44 through 60 is similar to the persistent response over disturbed water such as the open ocean. However, an explanation requiring the simultaneous presence of quiet and disturbed water is difficult to accept and especially so since the automatic gain control setting was more appropriate to a dry land than an open ocean footprint.

Deviations from the typical dry land waveform were noted in the waveforms of Figures 7 through 12. Examination of the maps revealed that the footprints associated with these waveforms contained a prominent surface feature such as a road, canal, or power line. Typical footprints did not have prominent features indicated on the maps. Many additional waveforms containing deviations were found in the data acquired during SEASAT's flight over Florida on pass 515, and a significant fraction of these was associated with footprints which contained prominent surface features. Therefore, we reasonably conjecture that the deviations in the waveforms were caused by the unusual features within the footprints. There was no attempt made to verify the existence of indicated features, or the presence of other features within the footprints by inspection of the terrain or by aerial photography. However, perusal of waveforms produced by the SEASAT radar altimeter, whether over ocean or land, demonstrated that the instrument normally generated waveforms which were uncluttered by noise or other spurious responses. Therefore, we believe that the frequent indication of unusual surface features in footprints associated with waveforms showing atypical responses means that the radar altimeter was affected by the surface features. The GEOSAT satellite, which is to be launched soon, will carry a radar altimeter which is essentially identical to the one carried aboard SEASAT. It will be interesting to examine waveforms generated by GEOSAT's altimeter along with footprint images obtained by timely aerial photography.

OCEAN TO LAND TRANSITIONS

The open ocean waveform shown in Figure 14 is unusual because of the enhanced response near gate 45. Brooks (1983) interpreted this enhancement as energy reflected from the shore while the satellite was still over the ocean. Brooks noted that the shoreline could first be detected when the sub-satellite point was 4.8 km from the shore, which would place the enhanced response in gate 61. As the satellite moved toward shore, the enhanced response would move into earlier gates and appear in the central gate as the satellite passed over the shoreline. Based on the presence of

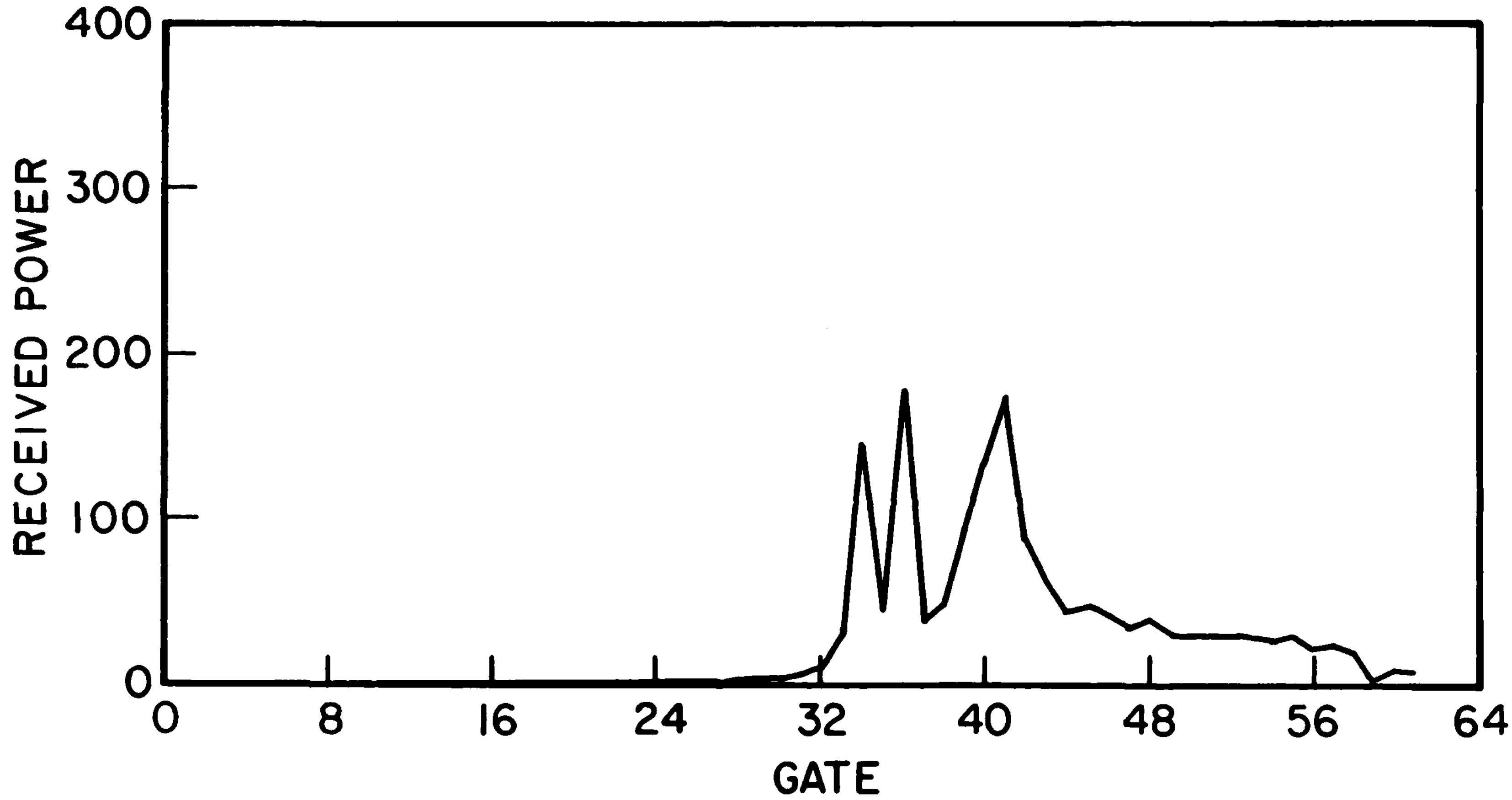

Fig. 13 No satisfactory explanation has been found for this unusual waveform.

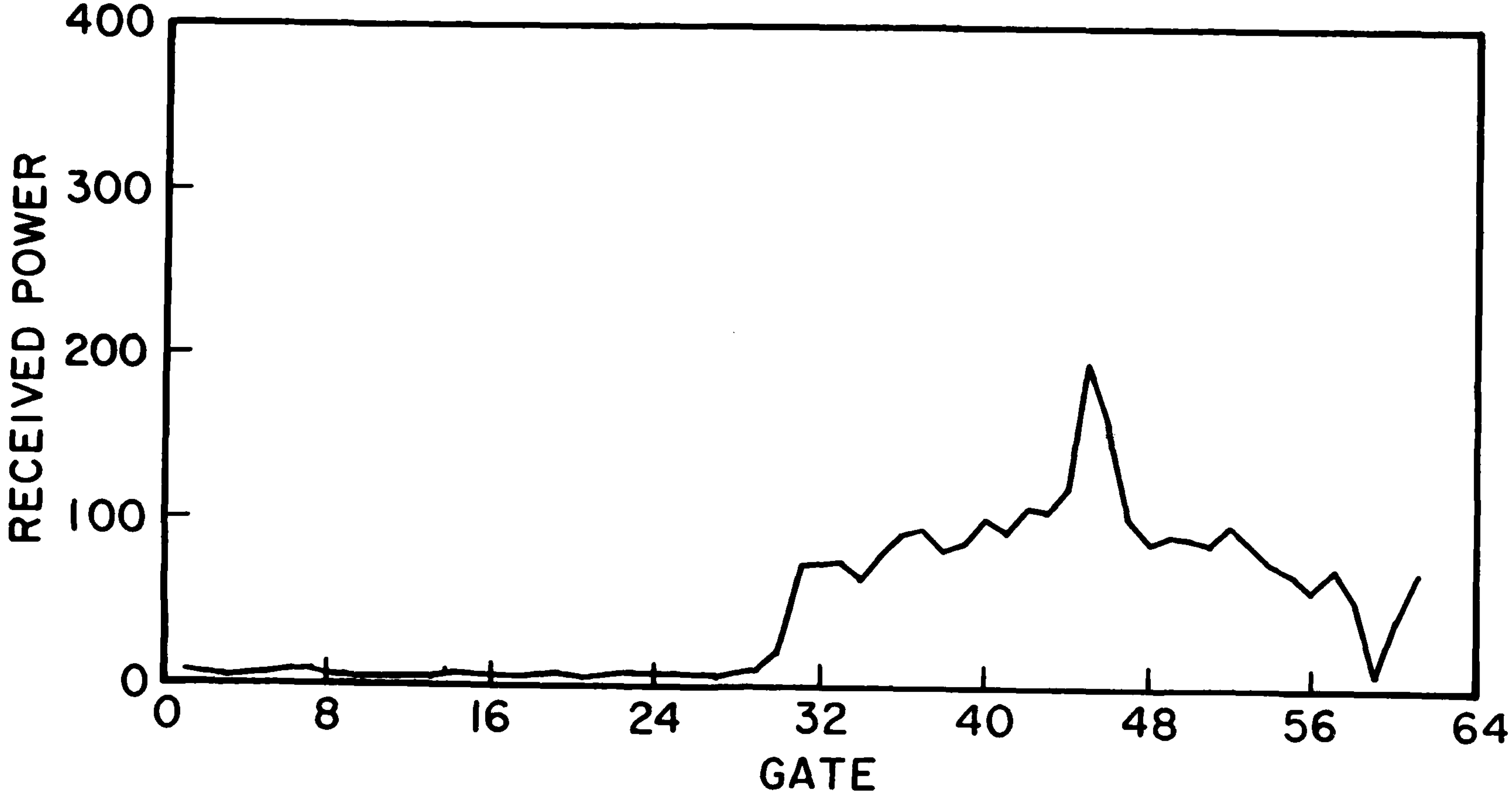

Fig. 14 The sharp peak near gate 45 of this open ocean waveform is caused by the Florida shoreline which is approximately 3 km from the sub-satellite point.

the enhanced reflection in gate 45, the shore was approximately 3.2 km from the sub-satellite point. The sub-satellite points for the data transmissions bracketing the pulses for this waveform were at 28.239°N, 80.567°W, and 28.233°N, 80.569°W. Reference to the Tropic, Florida map shows that the sub-satellite point moved from 3.3 to 3.0 km offshore from Patrick Air Force Base during the acquisition of data for the waveform in Figure 14. It would be interesting to determine whether these shore signatures in the ocean waveforms can be used to distinguish a sloping beach from a steep cliff, or other significant characteristics.

SUMMARY AND RECOMMENDATIONS

It has been conclusively demonstrated, through our effort and the efforts of other researchers, that the radar altimeter aboard the SEASAT satellite could accurately measure ground elevation over relatively flat terrain. Brooks, in particular, has been able to put this capability to good use for measuring ground subsidence (Krabill and Brooks, 1979; Brooks, 1981a), defining the extent of ice fields and establishing a reference height profile for use in determining whether they are growing or melting (Brooks, et al., 1982; Brooks and Norcross, 1982, 1983a), measuring water levels in remote lakes (Brooks, 1982), and terrain profiling in remote regions (Brooks, 1980, 1981b; Brooks and Norcross, 1983b). In addition to the demonstrated capability to measure ground elevation, the instrument may have had some capability to detect surface features such as canals, elevated roads, and power lines. However, measurements were limited to flat regions because the design of the radar altimeter had been optimized for operation over the ocean.

Analysis of the data and waveforms obtained from the SEASAT radar altimeter while over land should continue. The capability to measure surface elevations can be refined and could be automated. Additional understanding is needed of the interaction of the radar pulses with solid ground and, from that, the location and extent of the footprint in various types of terrain. The possibility that surface features can be distinguished in the waveforms should be pursued. If this capability can be verified, skill in interpreting the waveforms should be developed. The inverse scattering process is inherently non-unique to be sure. However, when the altimeter waveform is used in a synergetic way with observations from other types of sensors, valuable information can be obtained. An estimate should be made of the fraction of the Earth's surface which could be measured by the radar altimeter as configured on SEASAT. Specific land areas for which good data were obtained should be identified.

The radar altimeter carried aboard SEASAT was a relatively simple instrument with simple data processing requirements. An effort should be made to identify design modifications which will result in better performance over land. An improved instrument can easily be designed to determine whether the satellite is over land or over water based on the significant differences in the typical waveforms and the automatic gain control settings. Therefore, it could automatically switch between a mode optimized for ocean measurements and a mode modified for land measurements.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions to this effort by R. Whitman and K. McMillin, formerly with Bendix Field Services Company. Mr. Whitman wrote the computer programs to format and display the radar altimeter data obtained while the SEASAT was over the ocean. Ms. McMillin analyzed Mr. Whitman's programs and then modified them to facilitate display and analysis of the overland data. She also identified preliminary waveform categories and sorted the large number of waveforms from pass 515 according to category. The authors also thank J. Shuhy of Bendix Field Services Company and Dr. Lee Miller of the Applied Science Associates for reviewing the manuscript and constructive criticism. Finally, the encouragement and support from Dr. Vincent Noble is gratefully appreciated.

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